Overview of the Aerothermodynamics Analysis Conducted in Support of the STS-107 Accident Investigation

April, 2004

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NASA Johnson Space Center

and et. al

Aero/Aerothermo/Thermal Organization

- Multi-Center / Multi-Organization Team has been formed in support of the Columbia accident investigation.
  - NASA –JSC
  - NASA – LaRC
  - NASA – Ames
  - NASA – MSFC
  - Boeing – Houston
  - Sandia National Labs.
  - Boeing – Huntington Beach
  - Lockheed-Martin – Houston
  - Boeing – Phantom Works
  - Boeing – Rocketdyne
  - Air Force Research Lab. (WPAFB)

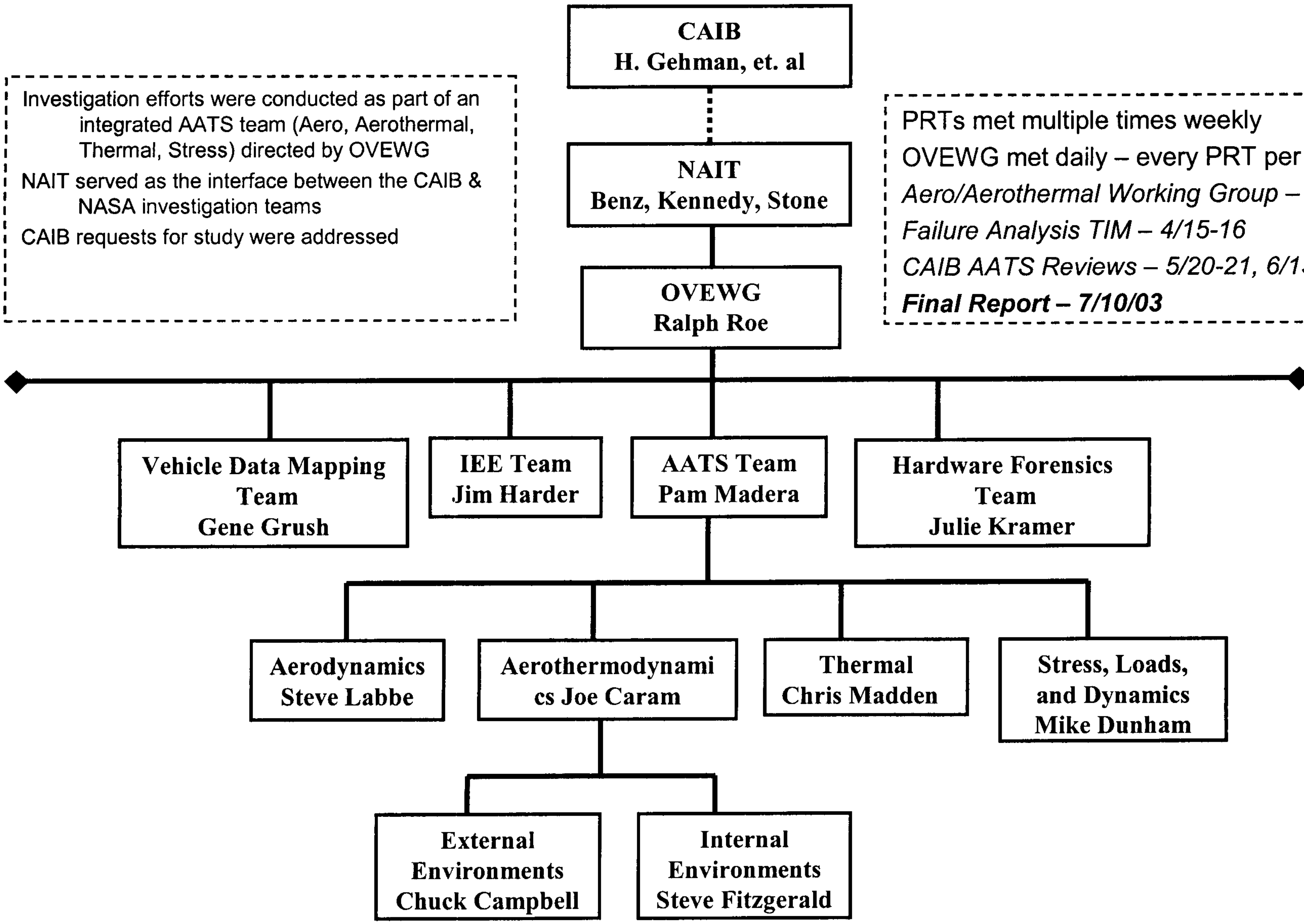
- Technical Areas of Support:
  - Aerodynamics analysis
  - Aerothermodynamics analysis
  - Computational Fluid Dynamics
  - Direct Simulation Monte Carlo
  - Wind Tunnel Testing
  - Plume Modeling
  - Venting
  - Thermal Structure Analysis
  - TPS & Structural Materials Analysis
  - TPS & Structural Materials Testing
  - Coupled Venting/Thermal Analysis

Investigation Organization

Investigation efforts were conducted as part of an integrated AATS team (Aero, Aerothermal, Thermal, Stress) directed by OVEWG

NAIT served as the interface between the CAIB & NASA investigation teams

CAIB requests for study were addressed



PRTs met multiple times weekly

OVEWG met daily – every PRT per week

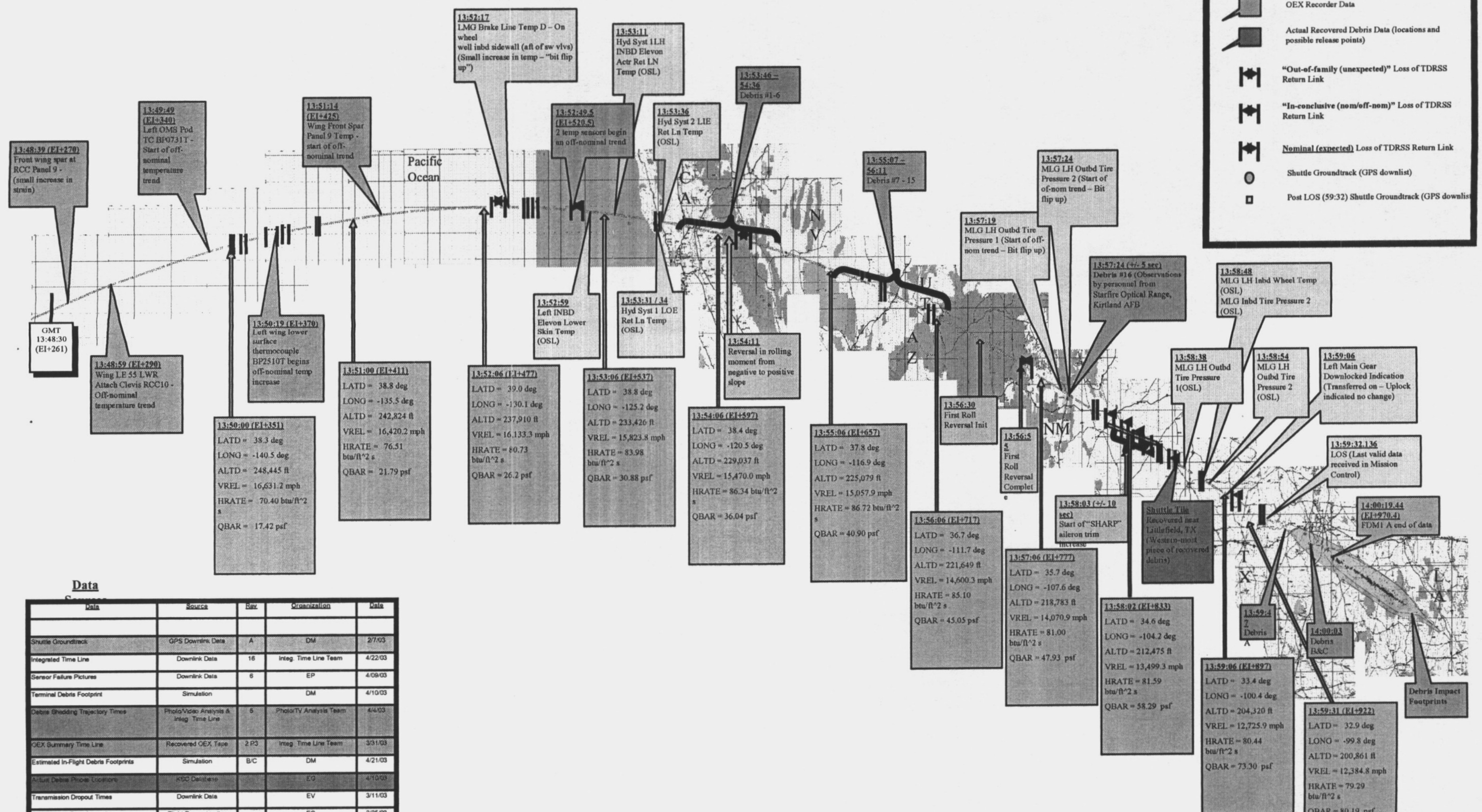
Aero/Aerothermal Working Group – 4/9-11

Failure Analysis TIM – 4/15-16

CAIB AATS Reviews – 5/20-21, 6/13 & 6/26

Final Report – 7/10/03

STS-107 Entry Trajectory and Timeline (1st Off-nominal event to Post-LOS) – REV D – 4/25/03



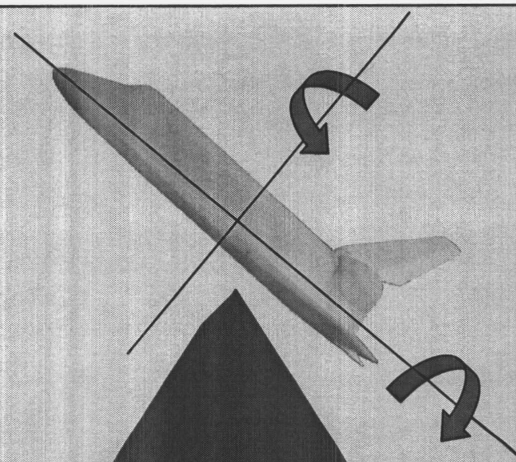
Data Sources

Data	Source	Rev	Organization	Date
Shuttle Groundtrack	GPS Downlink Data	A	DM	2/7/03
Integrated Time Line	Downlink Data	16	Integ. Time Line Team	4/22/03
Sensor Failure Pictures	Downlink Data	6	EP	4/09/03
Terminal Debris Footprint	Simulation		DM	4/10/03
Debris Shedding Trajectory Times	Photo/Video Analysis & Integ. Time Line	5	Photo/TV Analysis Team	4/4/03
OEX Summary Time Line	Recovered OEX Tape	2 P3	Integ. Time Line Team	3/31/03
Estimated In-Flight Debris Footprints	Simulation	B/C	DM	4/21/03
Actual Debris Phase Locations	KSC Database		EG	4/10/03
Transmission Dropout Times	Downlink Data		EV	3/11/03
Aerodynamic Data Anomalies	Flight Reconstruction		EG	2/25/03
Shuttle Trajectory Data	Flight Reconstruction		EG	3/10/03

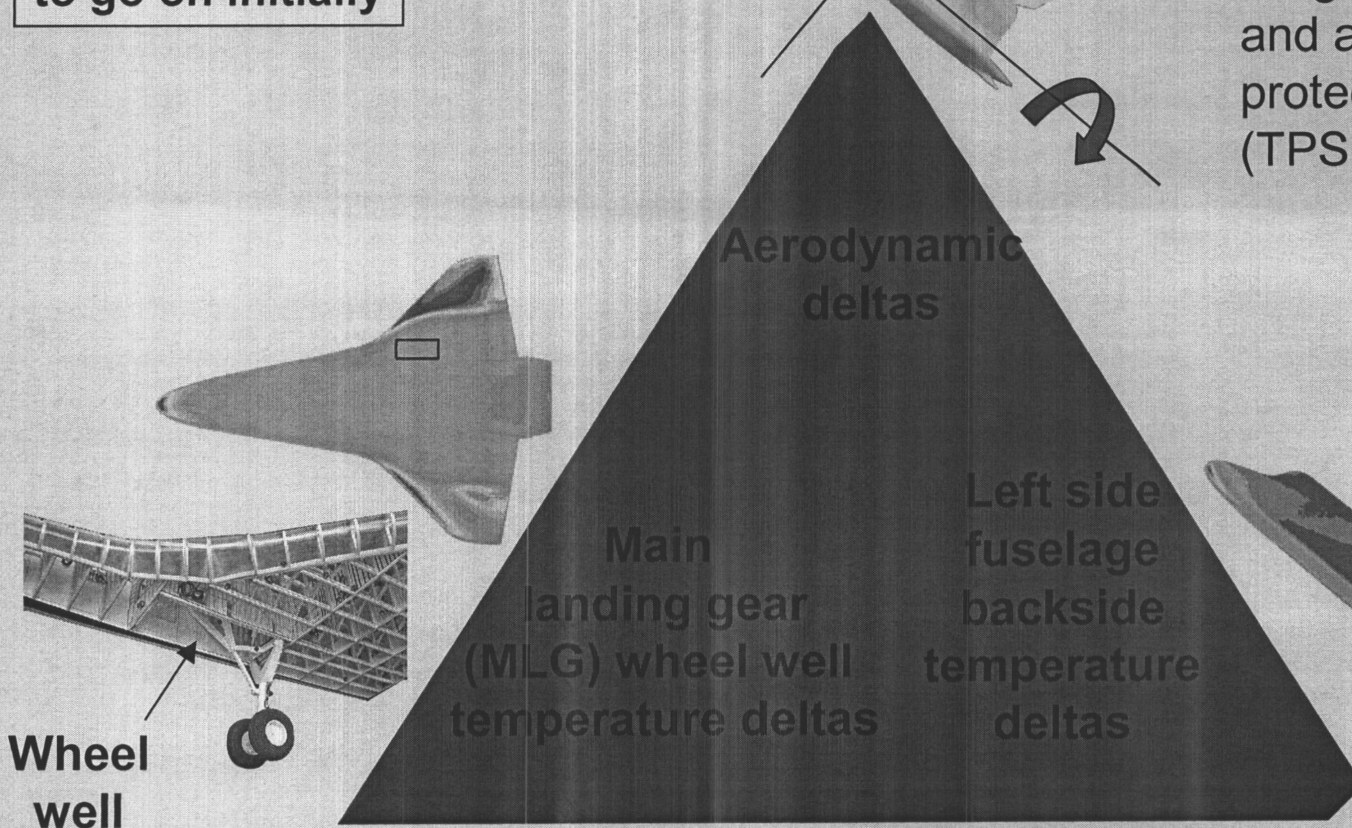
Produced by NASA/JSC - EG/Aeroscience and Flight Mechanics (J. Broome)

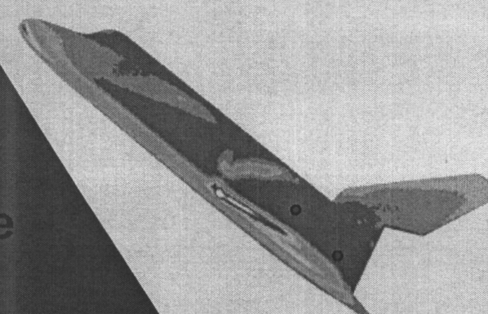
Indications from OI Telemetry Data

Relatively little information to go on initially

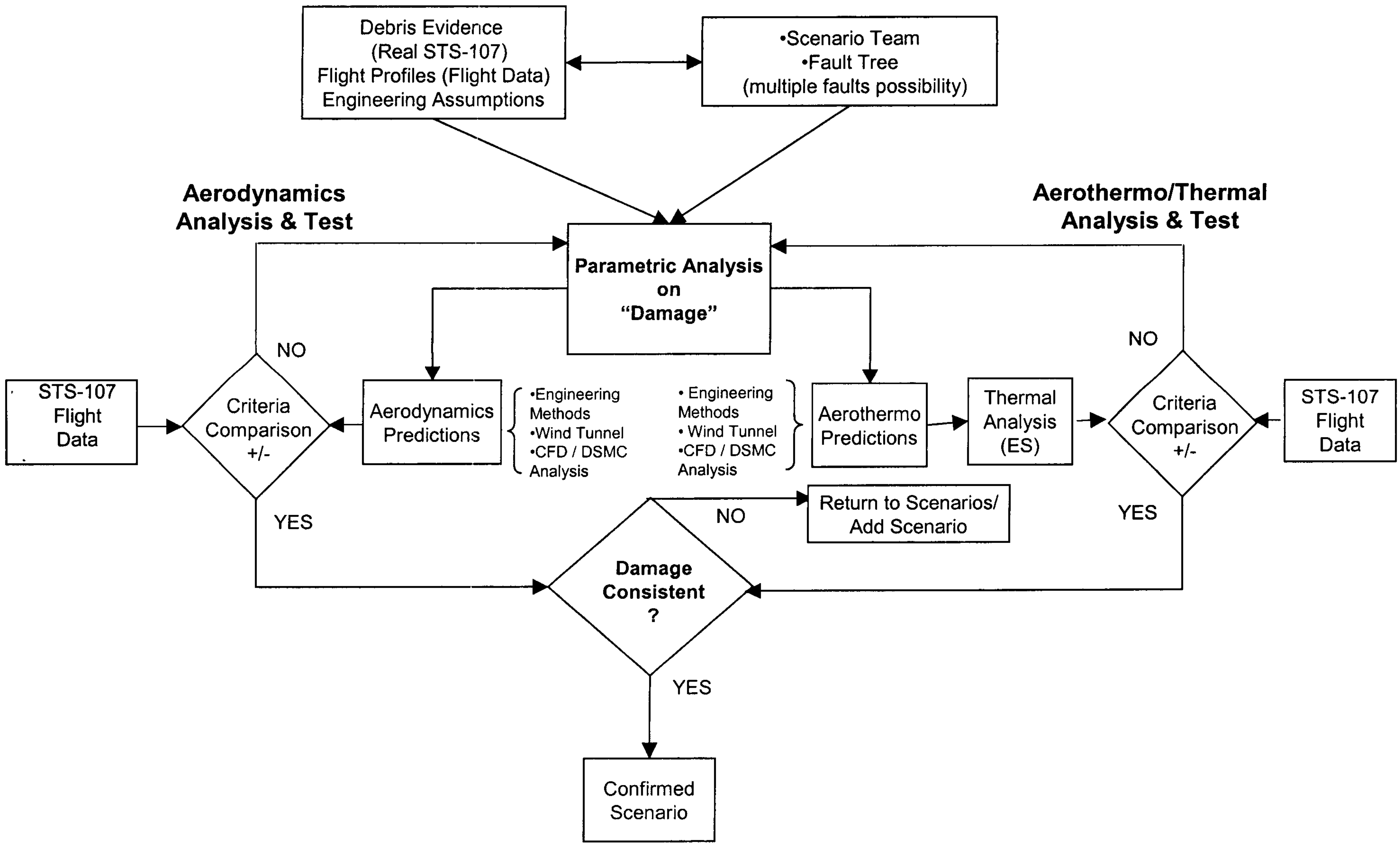


Motivation
Address failure scenarios involving wing leading edge and acreage thermal protection system (TPS) tile damage

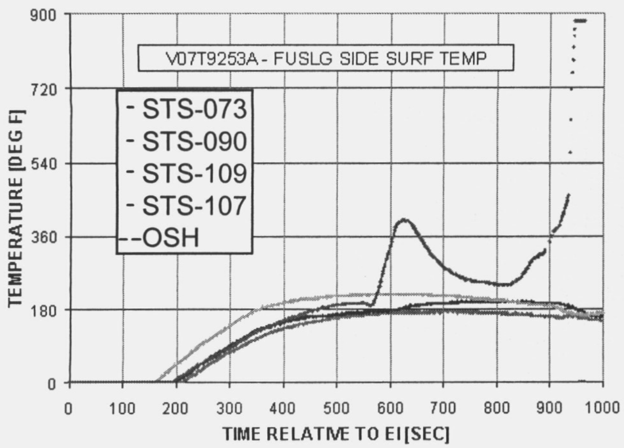


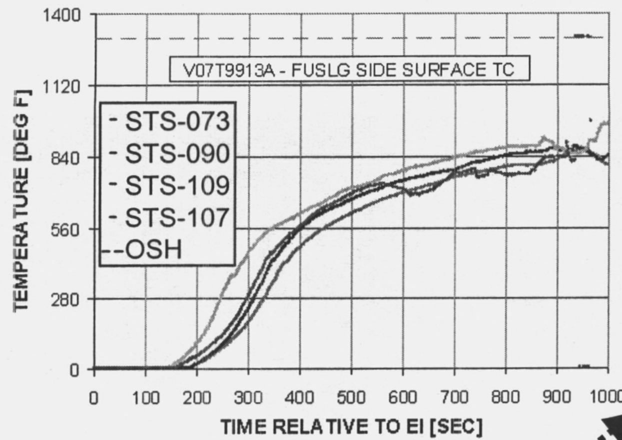


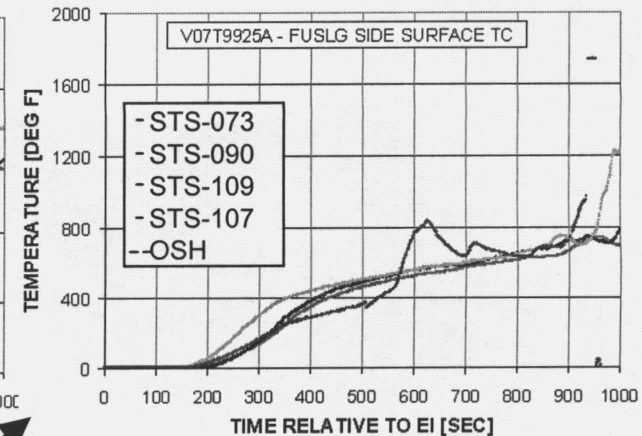
Aero/Aerothermo/Thermal Analysis Process

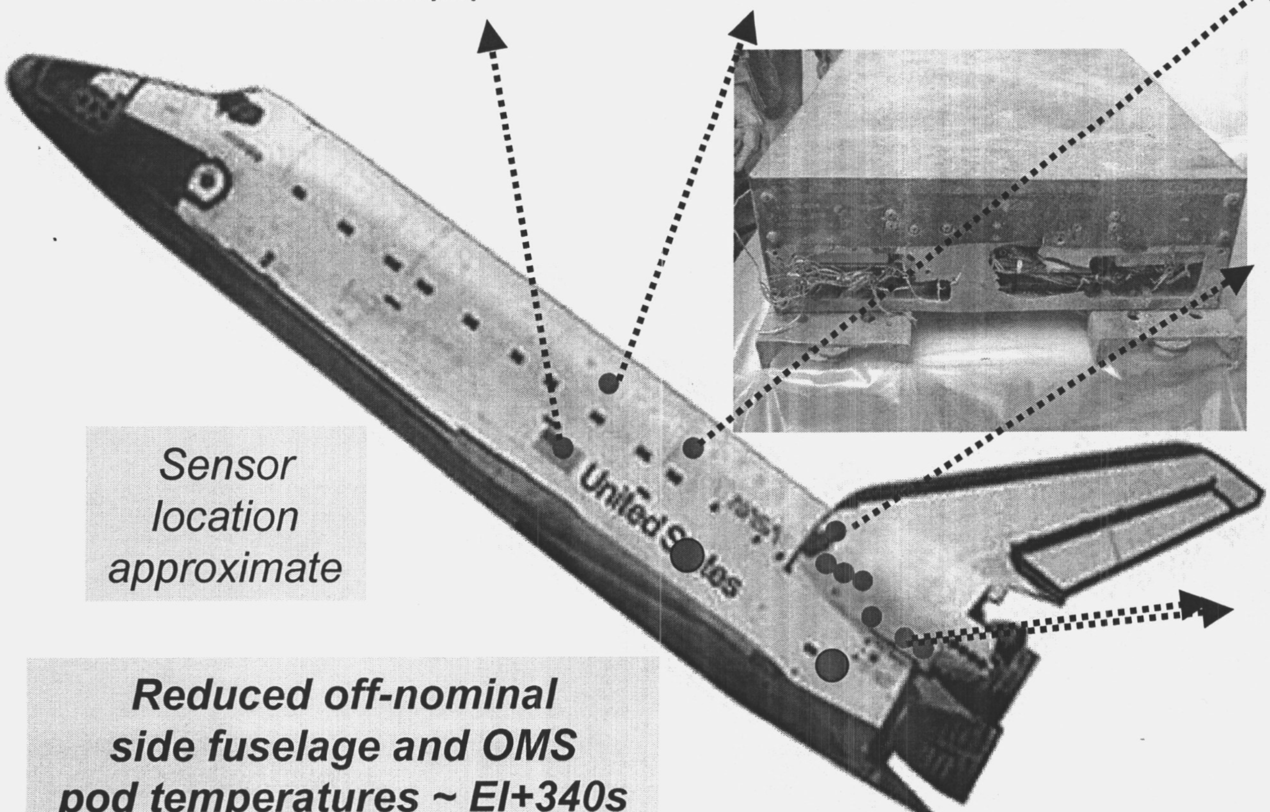


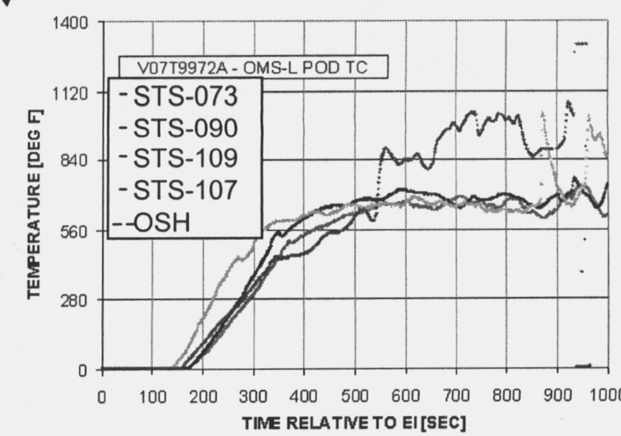
Selected STS-107 Side Fuselage/OMS Pod Off-Nominal Temperatures





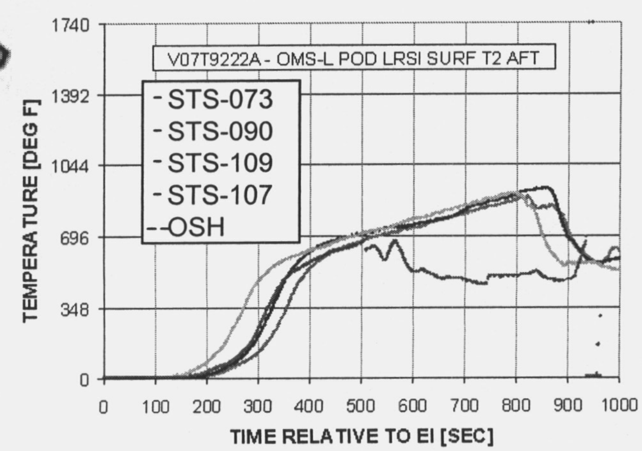




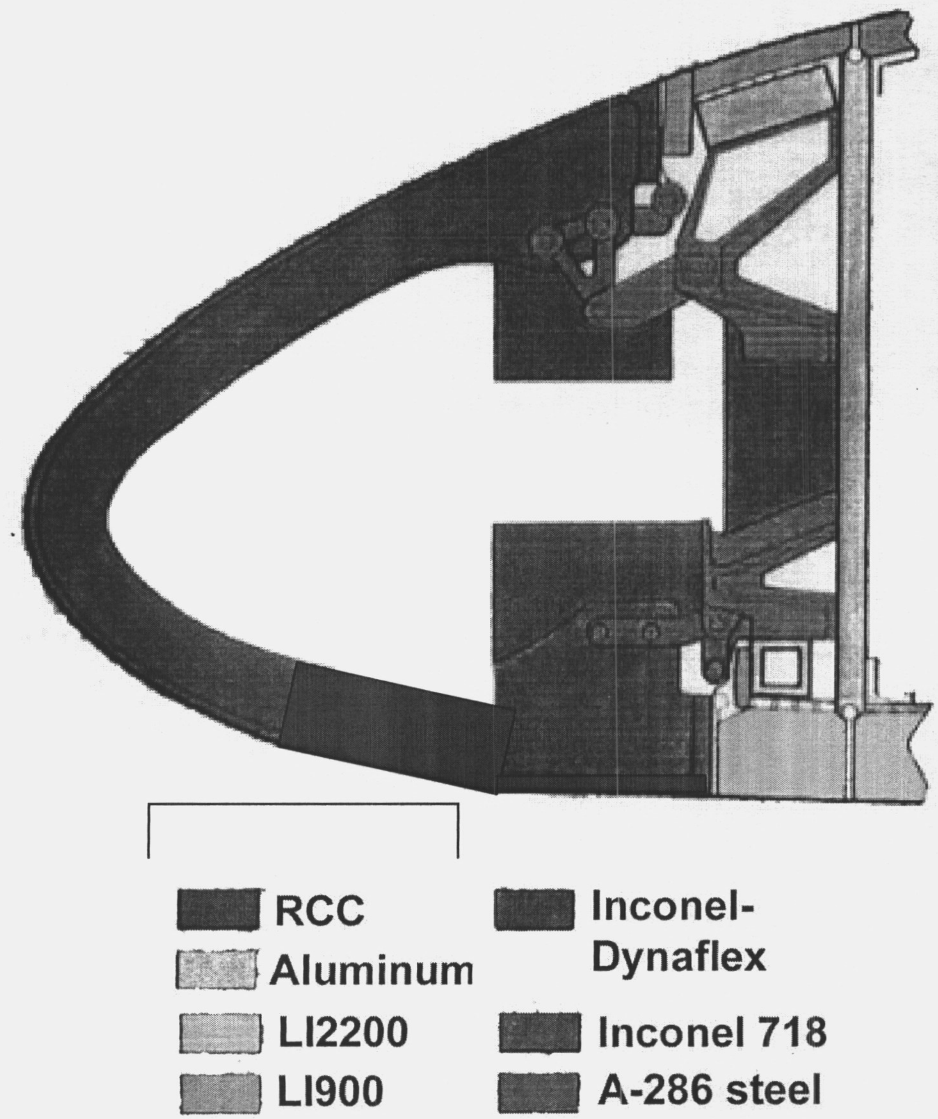


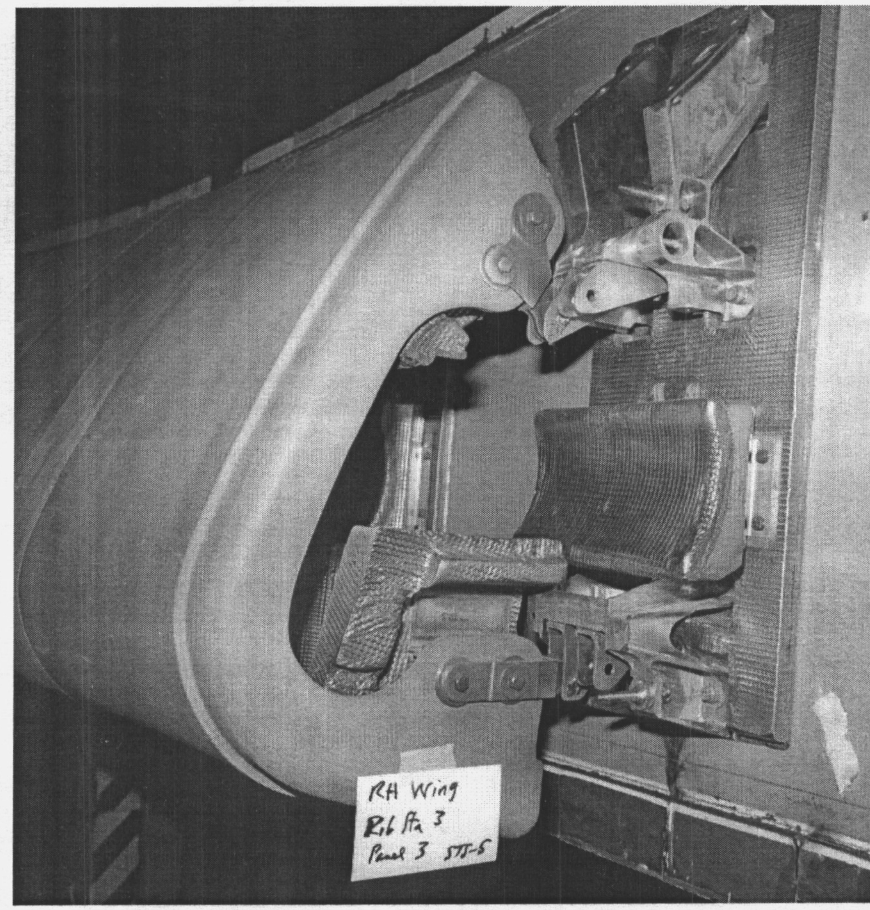
Sensor location approximate

Reduced off-nominal side fuselage and OMS pod temperatures ~ EI+340s



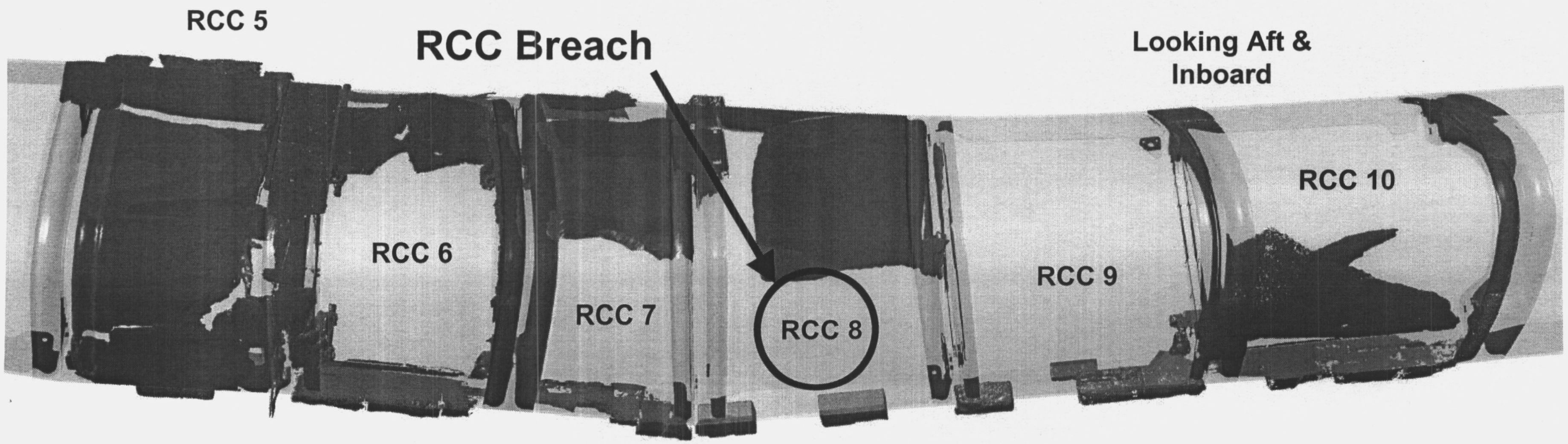
Leading Edge Structural Subsystem

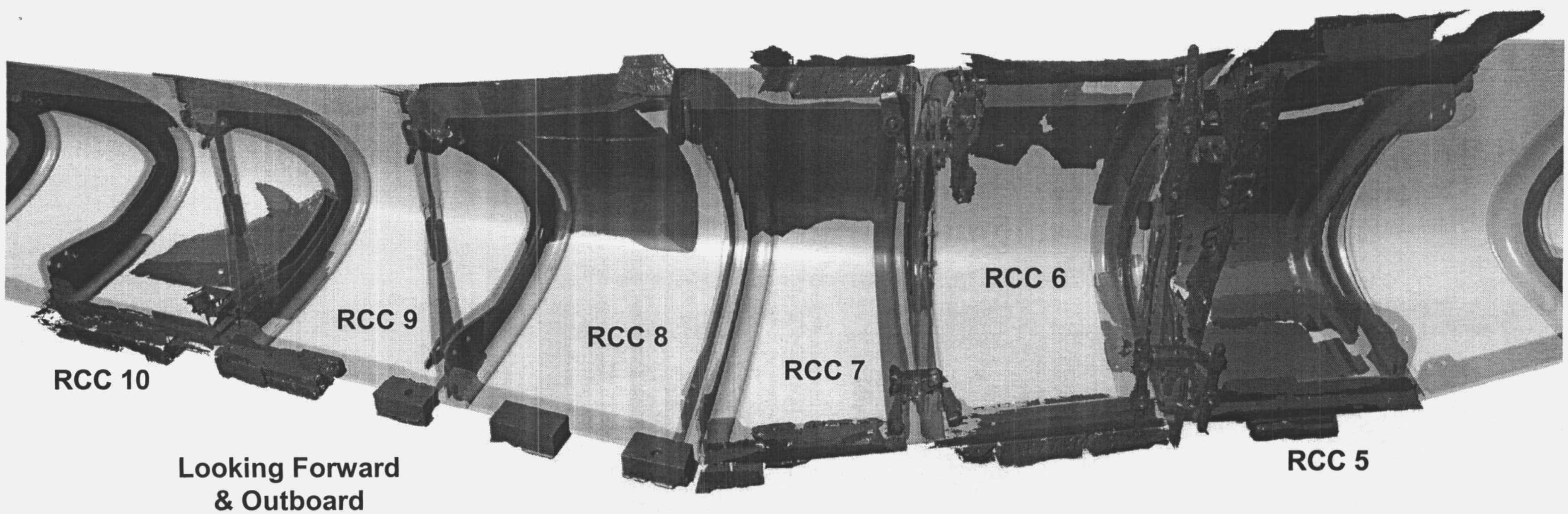




Relevant Forensics Evidence

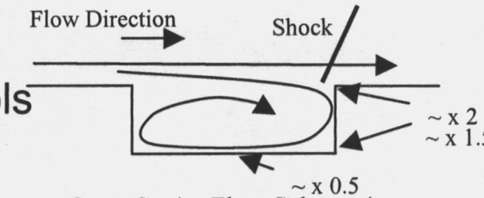
Scanned Debris In CAD Model & Forensics Team Conclusions



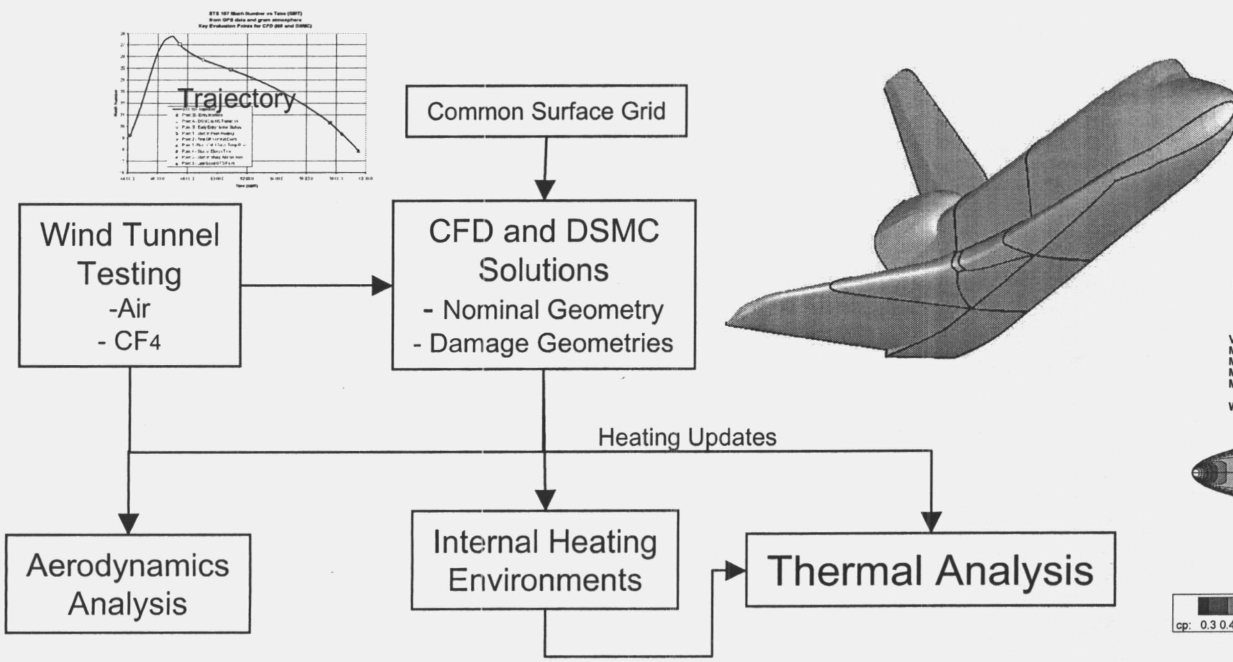


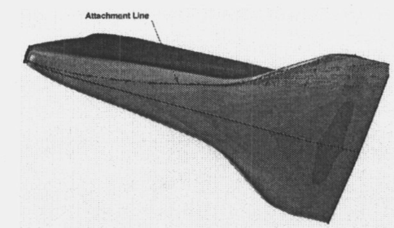
External Aerothermal Environments

- First Approach
  - Existing engineering and Orbiter specific heating analysis tools
  - Existing CFD and DSMC Solutions of the Orbiter
  - Wind Tunnel Testing
- Second Approach
  - Use of CFD and DSMC results of damaged Orbiter configurations will be used to confirm environments



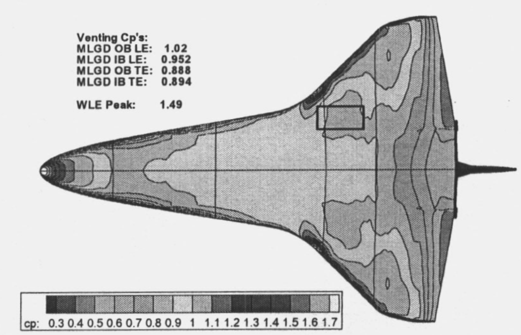
Open Cavity Flow Schematic
L/D < 14
e.g. Single Lost Tile



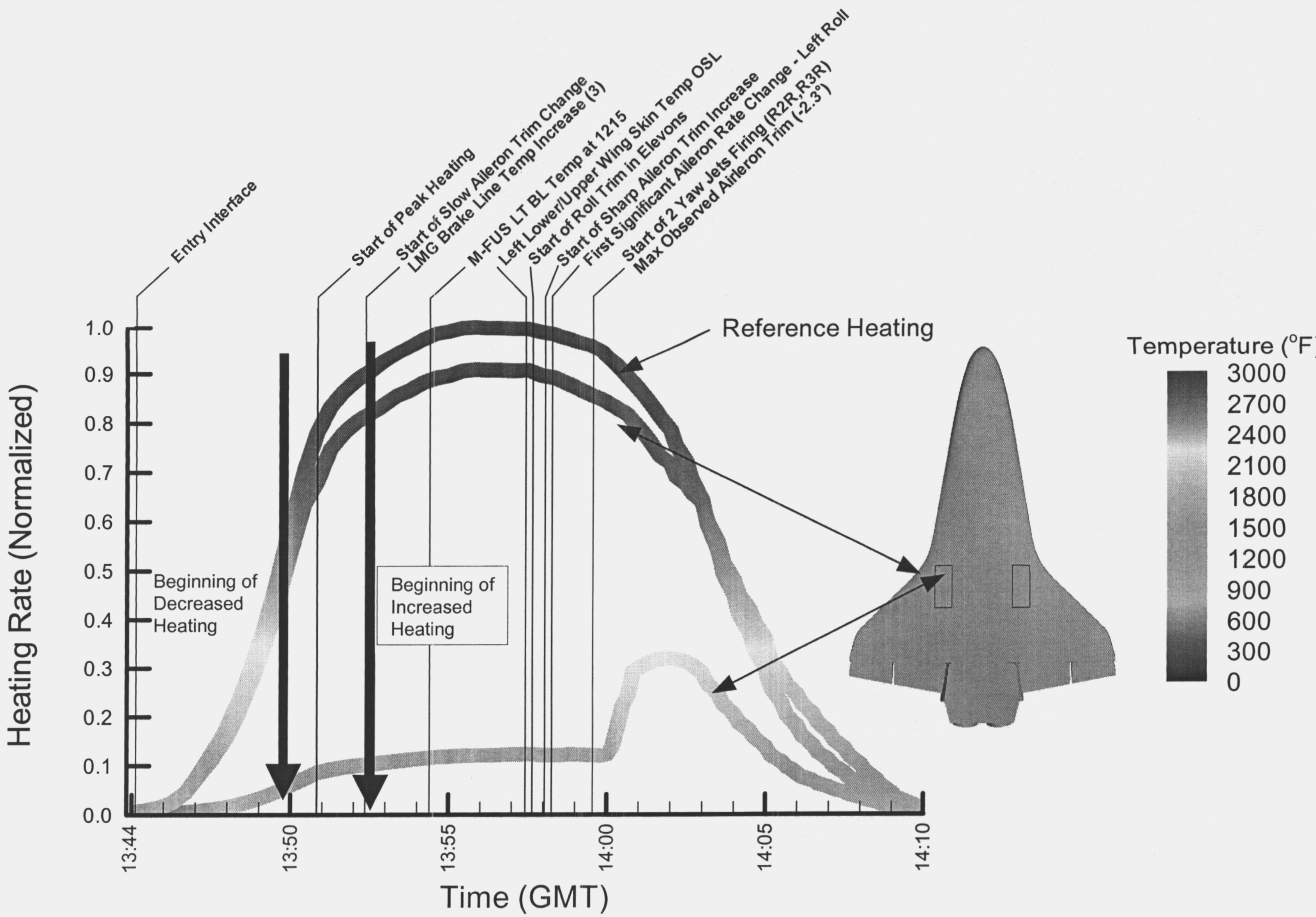


LaRC STS2 OEX LAURA Solution

M_∞=18.1, α=41.2°, $q_{bar\infty}$=2565 N/m², p_∞=11.23 N/m²



STS-107 Pre-Entry EOM3 Heating Profile

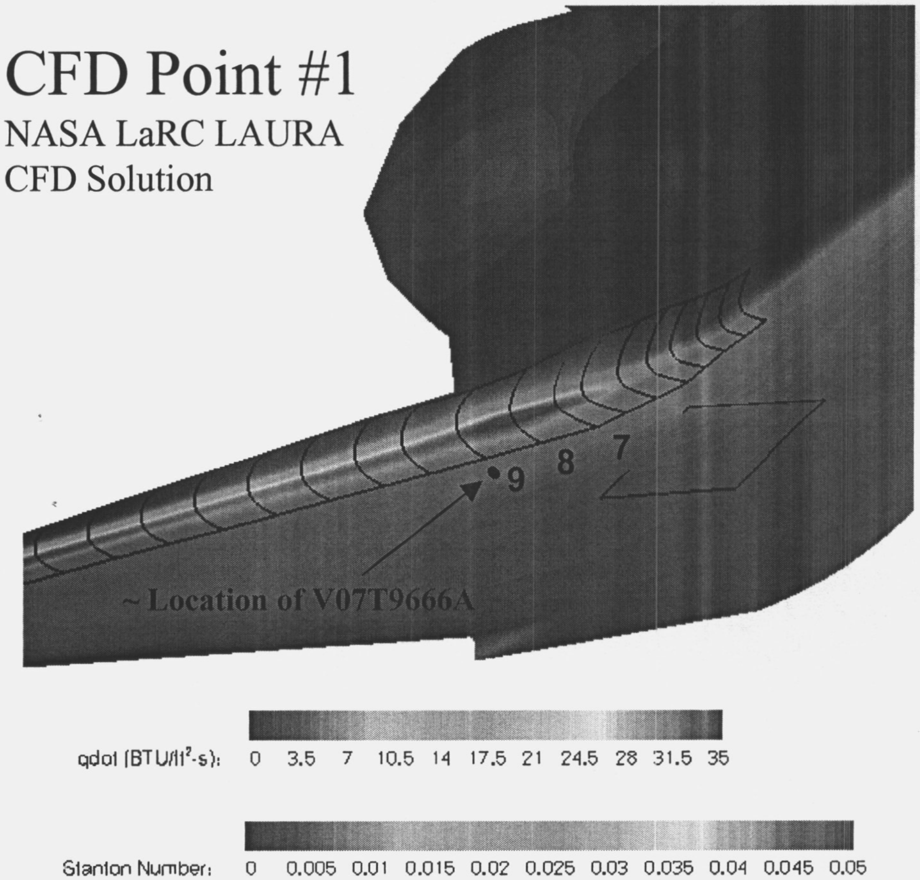


Surface Heating & Temperatures

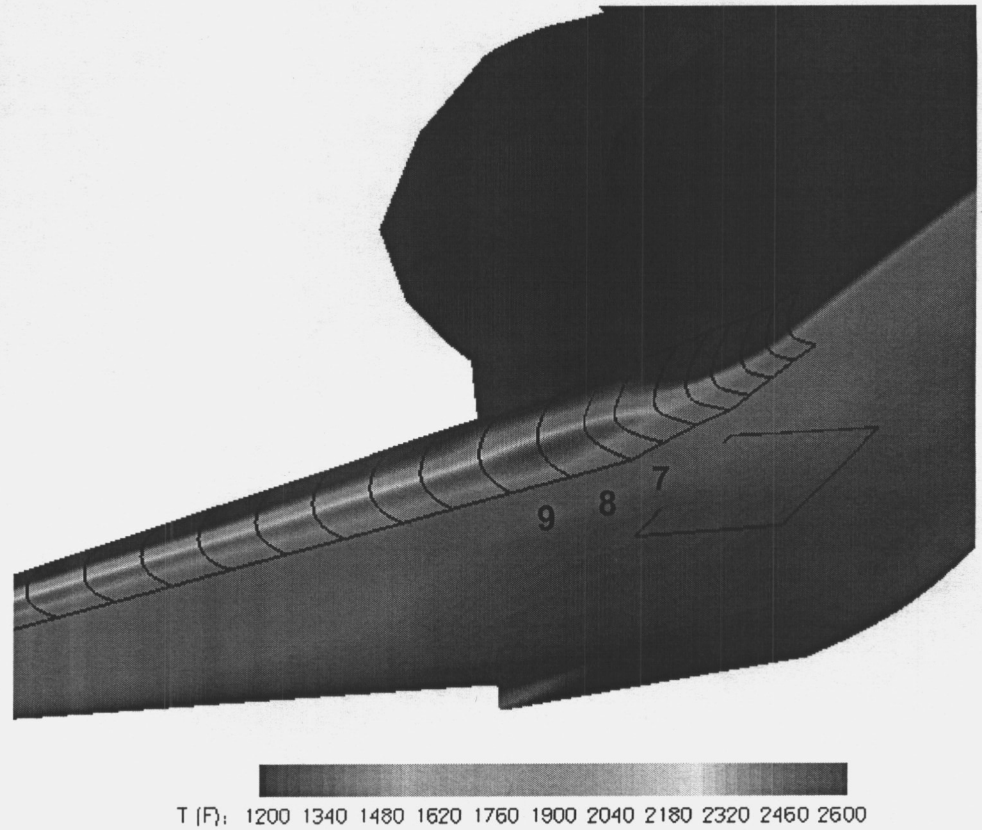
Radiation Equilibrium

CFD Point #1

NASA LaRC LAURA
CFD Solution



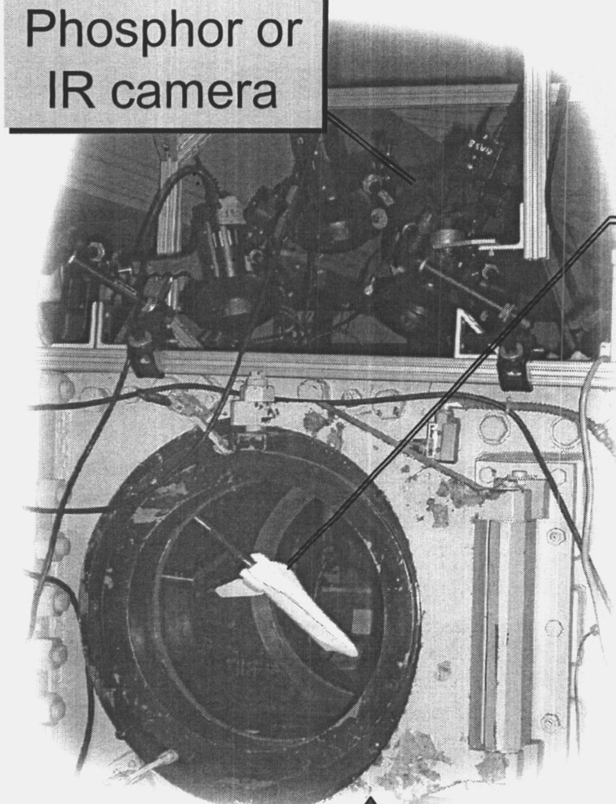
Heat Flux & Stanton No.



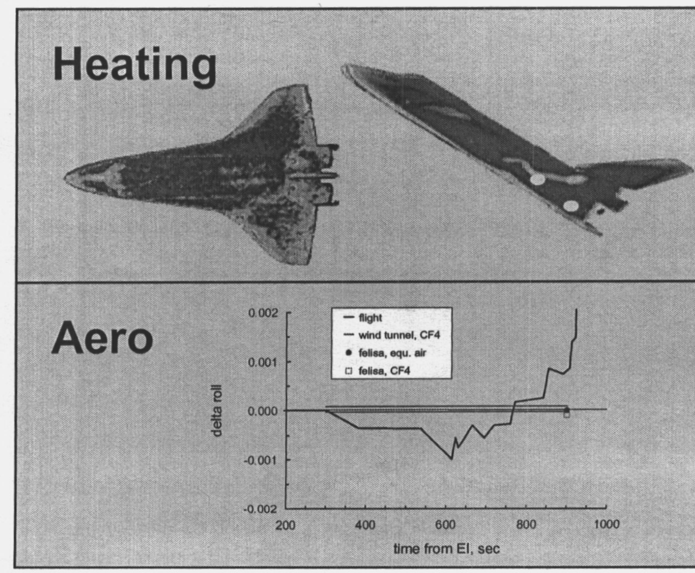
Temperatures, F

Orbiter Wing Leading Edge Damage Survey

Phosphor or IR camera



0.0075 scale ceramic Orbiter model



Typical cast ceramic wing leading edge with missing RCC panel

Shock interaction location RCC #9

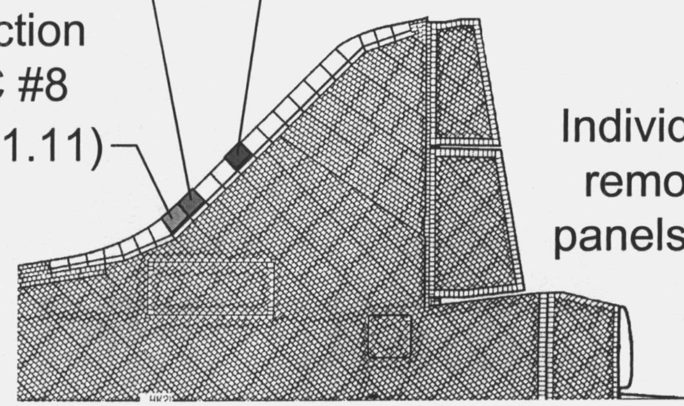
CF_4 (γ_{eff} = 1.13)

Shock interaction location RCC #8

Flight (γ_{eff} = 1.11)

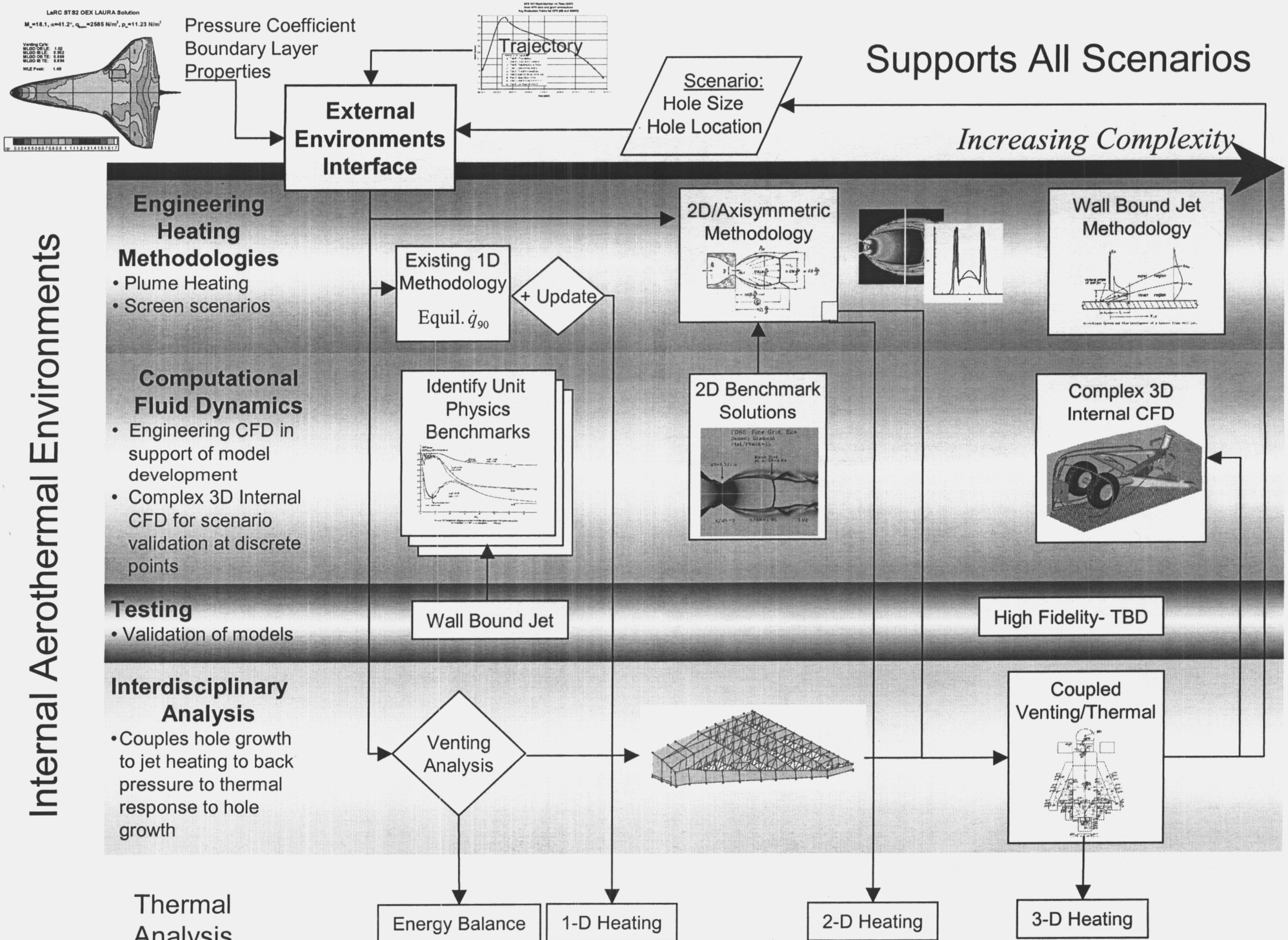
Shock interaction location RCC #12

Air (γ_{eff} = 1.4)

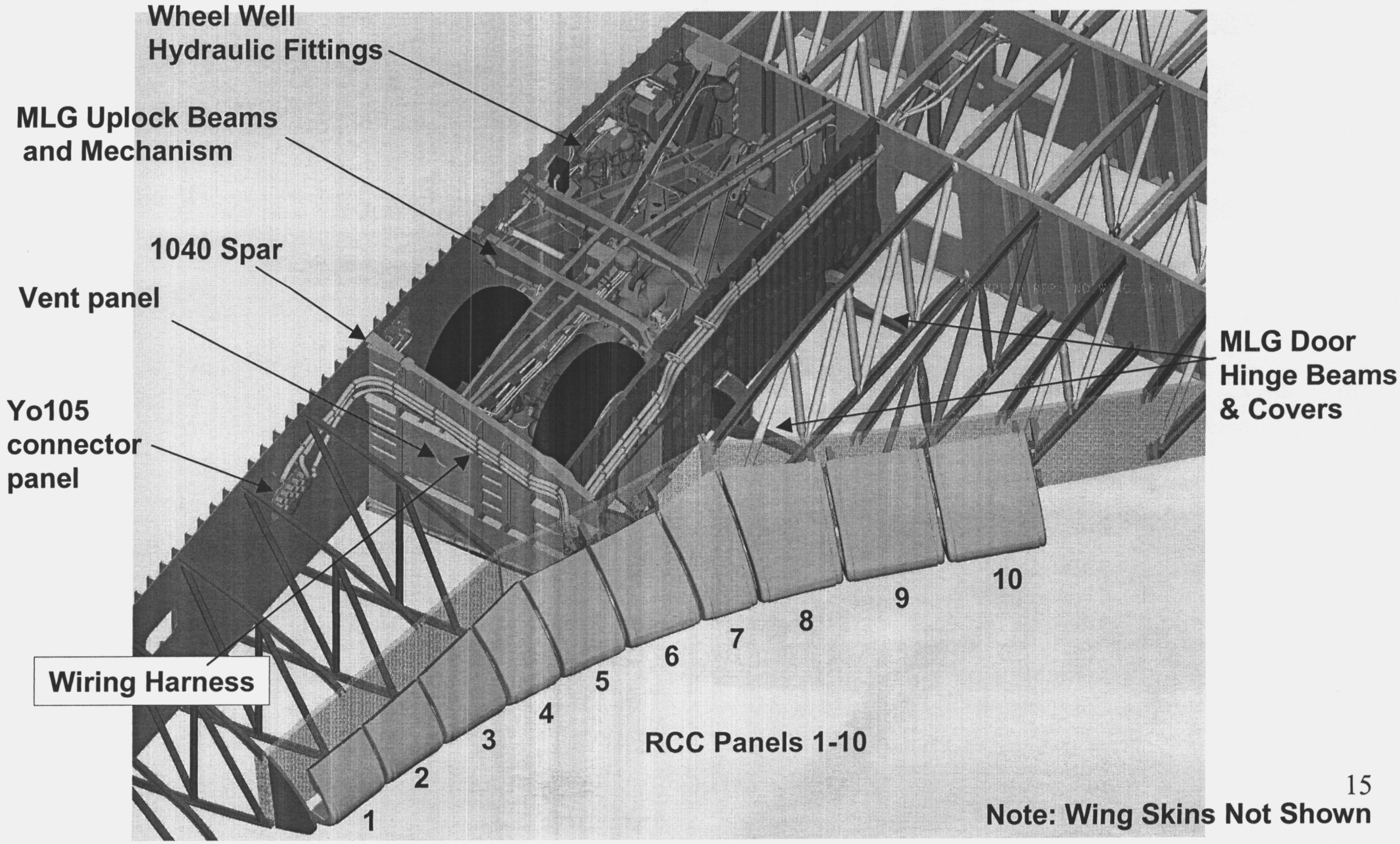


Individually removed panels 1-13

CAD definition provided by NASA JSC

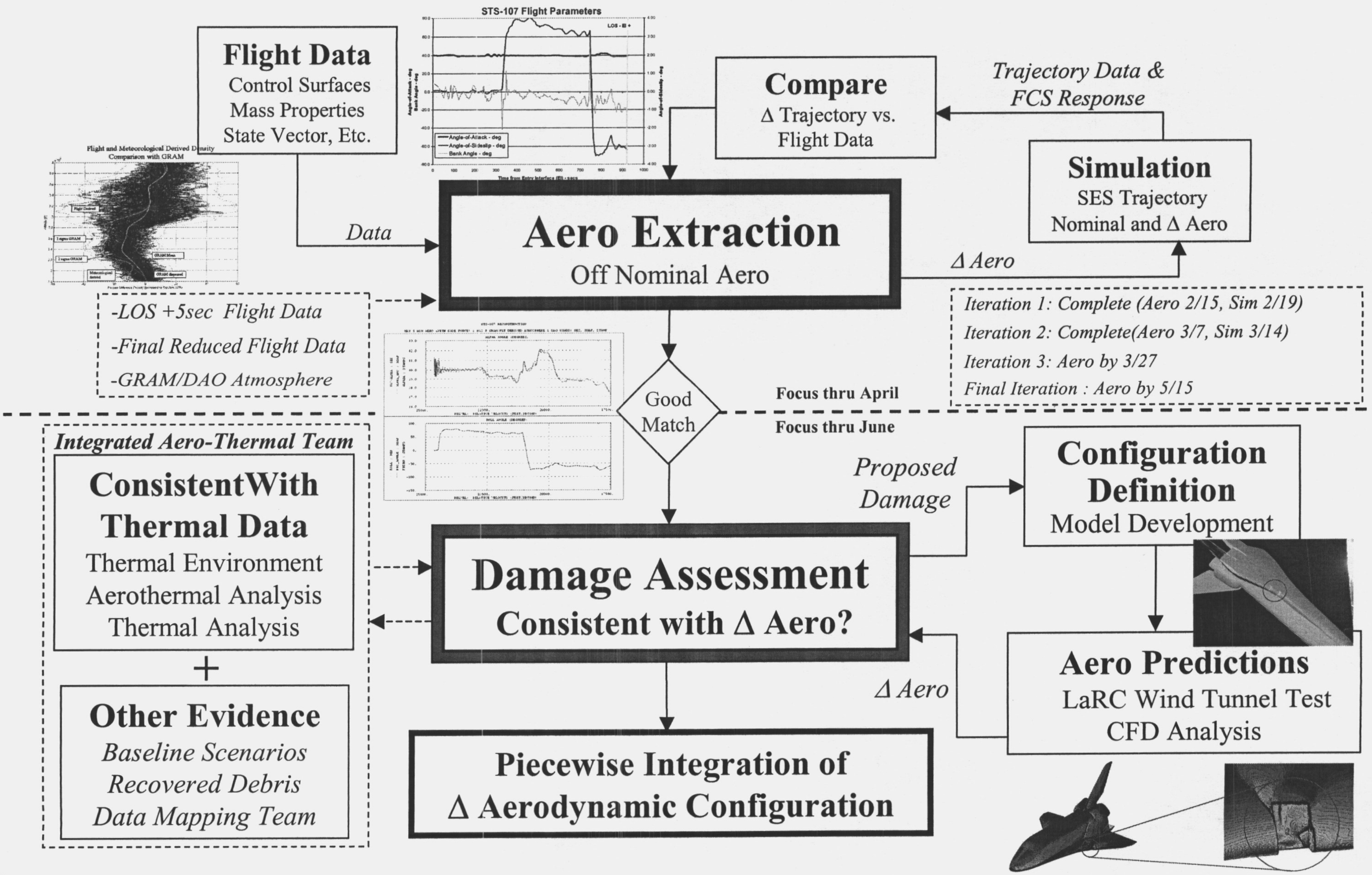

Internal Aerothermal Environments
LaRC STS2 OEX LAURA Solution
Pressure Coefficient
Boundary Layer
Properties
Trajectory
External Environments Interface
Scenario:
Hole Size
Hole Location
Supports All Scenarios
Increasing Complexity
Engineering Heating Methodologies
• Plume Heating
• Screen scenarios
Existing 1D Methodology
Equil. $\dot{q}_{90}$
+ Update
2D/Axisymmetric Methodology
Wall Bound Jet Methodology
Computational Fluid Dynamics
• Engineering CFD in support of model development
• Complex 3D Internal CFD for scenario validation at discrete points
Identify Unit Physics Benchmarks
2D Benchmark Solutions
Complex 3D Internal CFD
Testing
• Validation of models
Wall Bound Jet
High Fidelity- TBD
Interdisciplinary Analysis
•Couples hole growth to jet heating to back pressure to thermal response to hole growth
Venting Analysis
Coupled Venting/Thermal
Thermal Analysis
Energy Balance
1-D Heating
2-D Heating
3-D Heating

Orbiter Wing CAD Model

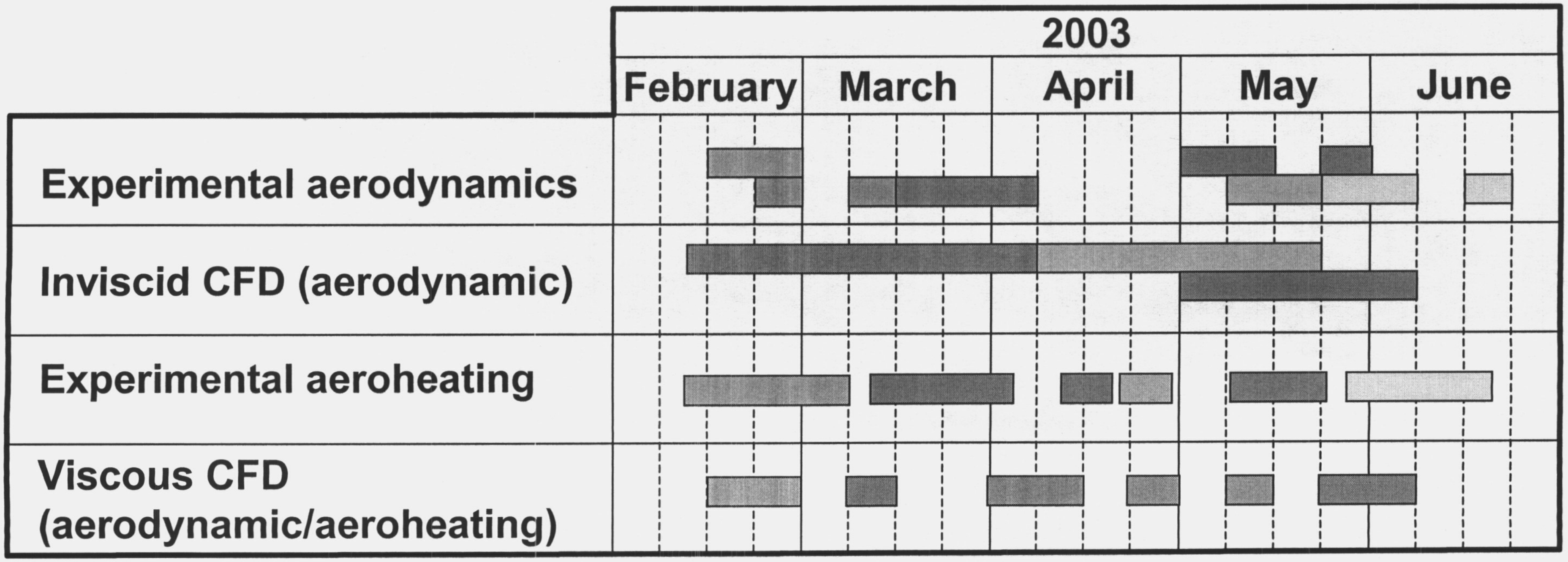


Note: Wing Skins Not Shown

Aerodynamic Flight Reconstruction



Chronology of Aerodynamic/Aerothermodynamic Contributions*



TPS tile damage; asymmetric boundary layer transition

Larger OML perturbations; missing left main landing gear door; deployed door; etc

Missing wing leading edge RCC panel (1 to 13); combinations of missing panels

Partial RCC panel missing; missing T-seal

Flow ingestion into RCC channel via breach in wing leading edge

Closure Cases

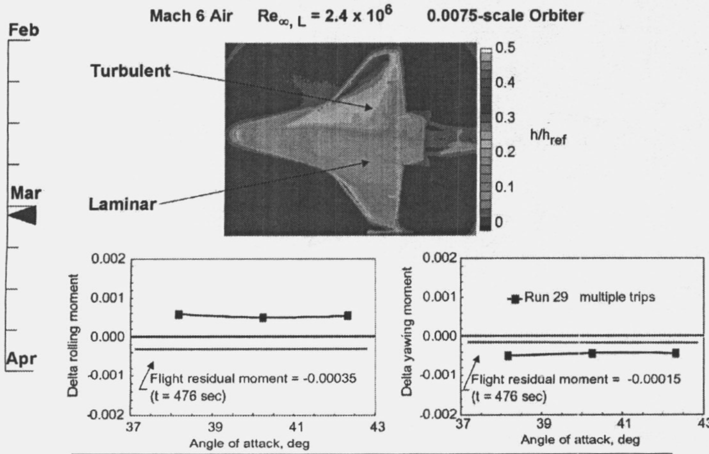
* Assessment of specific damage scenarios

Acreage TPS Tile Damage

Experimental Aerodynamics

Effects of Asymmetric Boundary Layer Transition on Aerodynamics

Mach 6 Air $Re_{\infty,L} = 2.4 \times 10^6$ 0.0075-scale Orbiter



Measured aerodynamic trends from ABLT inconsistent with extracted STS-107 flight

Brauckmann and Scallion

Brauckmann and Scallion

Experimental Aeroheating

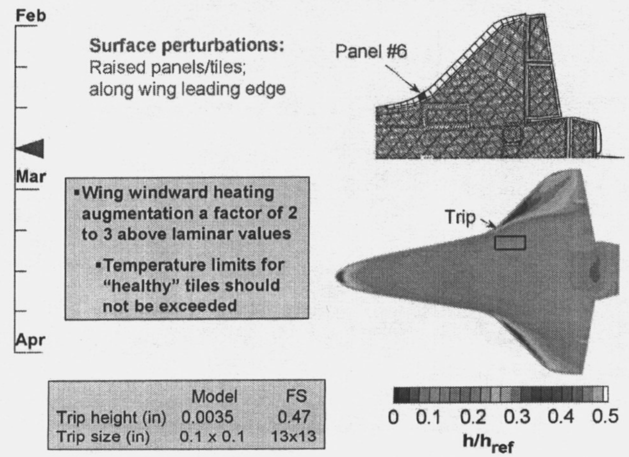
Effect of L.E. Roughness on Orbiter Nondimensional Heating

Mach 6 Air $\gamma_{eff} = 1.4$ $\alpha = 40$ deg $Re_{\infty,L} = 2.4 \times 10^6$ $\beta = 0$ deg

Surface perturbations:
Raised panels/tiles;
along wing leading edge

- Wing windward heating augmentation a factor of 2 to 3 above laminar values
  - Temperature limits for "healthy" tiles should not be exceeded

	Model	FS
Trip height (in)	0.0035	0.47
Trip size (in)	0.1 x 0.1	13x13

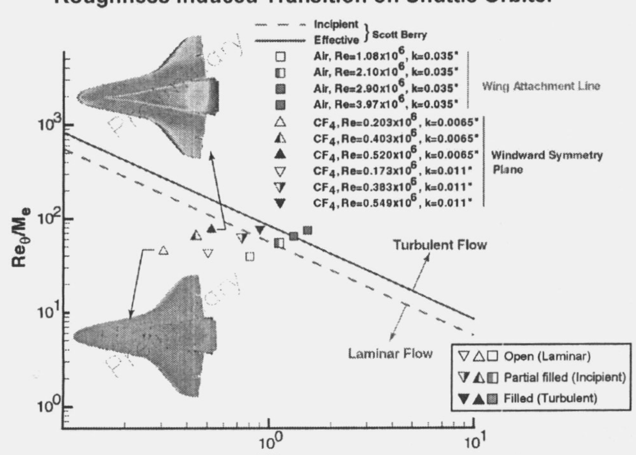


Horvath

Horvath

Inviscid CFD (Aerodynamic)

Roughness Induced Transition on Shuttle Orbiter



Hamilton, Weilmuenster, Wurster and Horvath

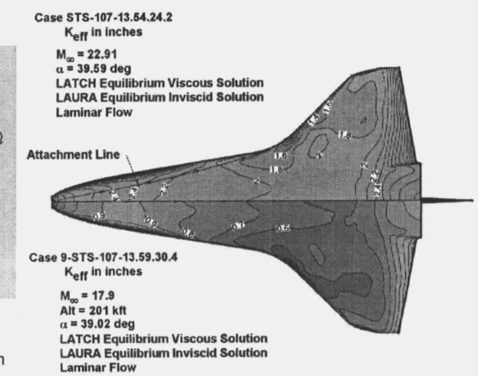
Viscous CFD (aerodynamic/aeroheating)

Effective Roughness Height Required to Cause Transition

BLT Prediction methodology based on discrete protuberance

- First BLT would occur @ approximately M=25, EI+400 sec for 2.5" protuberance
- Effective BLT would occur @ approximately M=24, EI+500 sec for 2.5" protuberance

K. Wurster/H. Hamilton



Hamilton, Horvath

Larger OML Perturbations

Experimental Aerodynamics

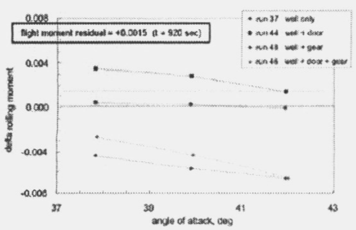
Large OML Change

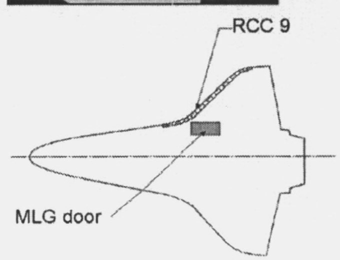
Effect of open wheel well, door deployed, landing gear deployed

Mach 6 Air $Re_{\infty,L} = 2.4 \times 10^6$ 0.0075-scale Orbiter

landing gear deployed

landing gear and door deployed





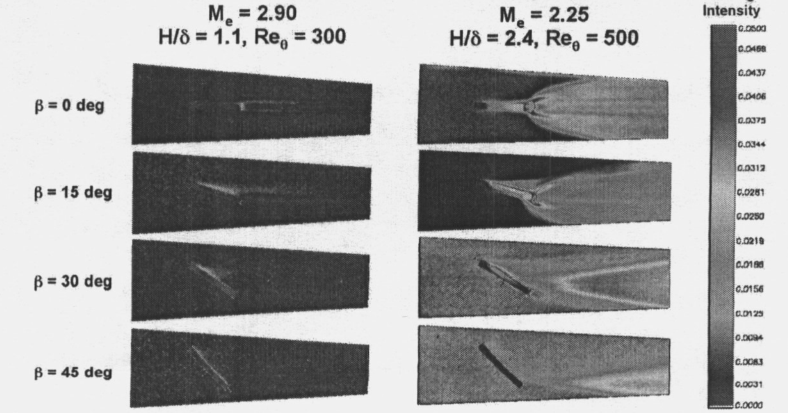
Brauckmann and Scallion

Experimental Aeroheating

SPACE SHUTTLE PROGRAM
Space Shuttle Vehicle Engineering Office
NASA Johnson Space Center, Houston, Texas

Cavity Orientation Effects L/H = 20, W/H=2.4, Untripped	Presenter/Org. Joel Everhart/LaRC	
	Date 11/18/03	Page 18

$M_e = 2.90$, $H/\delta = 1.1$, $Re_\theta = 300$ $M_e = 2.25$, $H/\delta = 2.4$, $Re_\theta = 500$

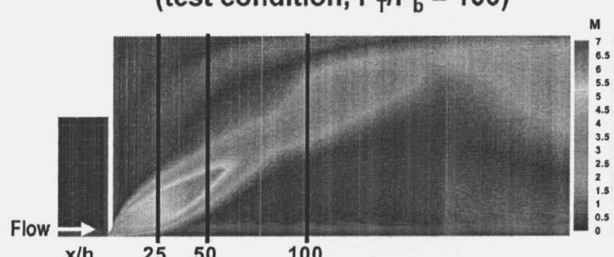


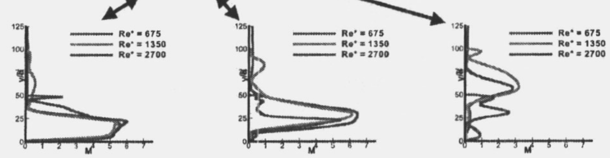
Everhart

Inviscid CFD

Viscous CFD (aerodynamic/aeroheating)

CFD Predictions of Mach Number Profiles for Lifted Supersonic Wall Jet (test condition, $P_T/P_b = 100$)

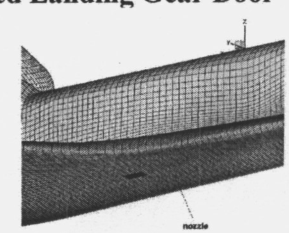


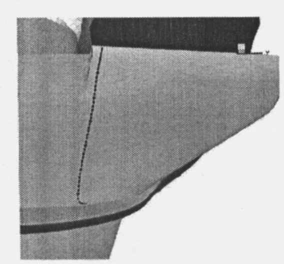


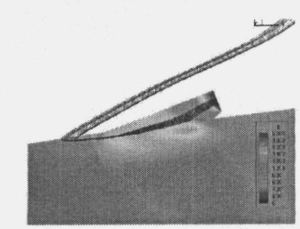
Glass

"Jet" Through Damaged Landing Gear Door

- Worst case estimate of stagnation conditions in bay produced ineffective side thrust and rolling moment with substantial part of jet entrained in boundary layer.





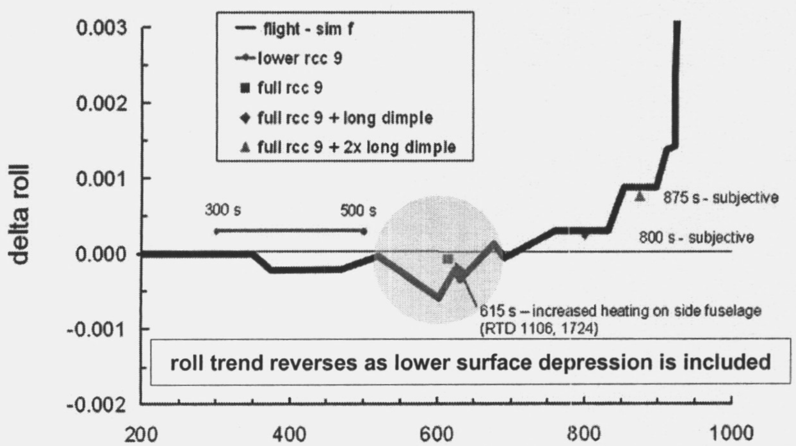


Gnoffo

Missing RCC Panel(s)

Experimental Aerodynamics

Progressive Damage Scenario - Roll



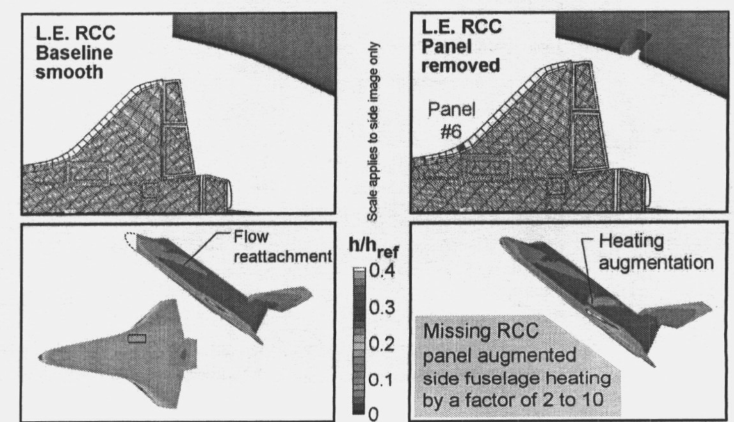
Brauckmann and Scallion

Experimental Aeroheating

Effect of RCC Panel 6 "Notch" on Orbiter Nondimensional Heating

NASA LaRC 20-Inch Mach 6 Air Tunnel

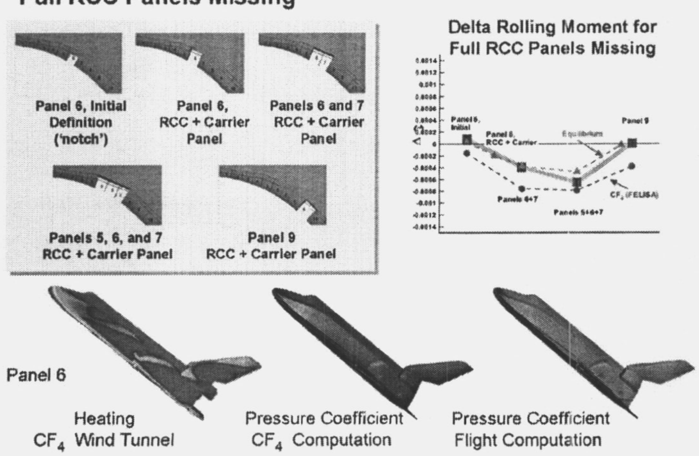
α = 40 deg $Re_{\infty, L} = 2.4 \times 10^6$ 0.0075 Scale



Horvath

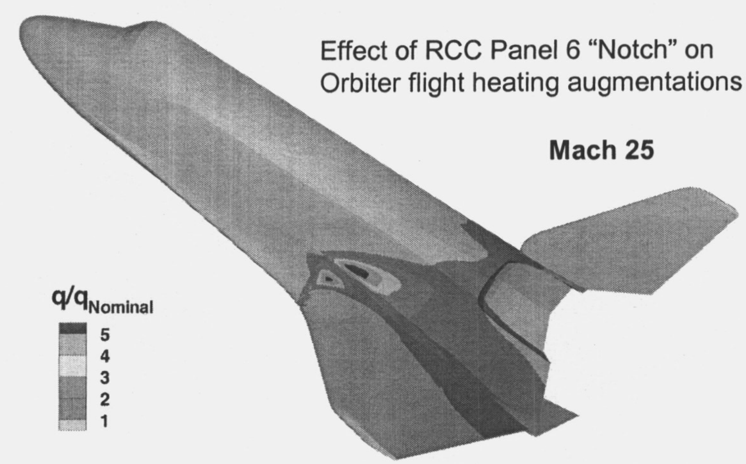
Inviscid CFD (Aerodynamic)

Computational Aerodynamics
Full RCC Panels Missing



Bibb

Viscous CFD (aerodynamic/aeroheating)

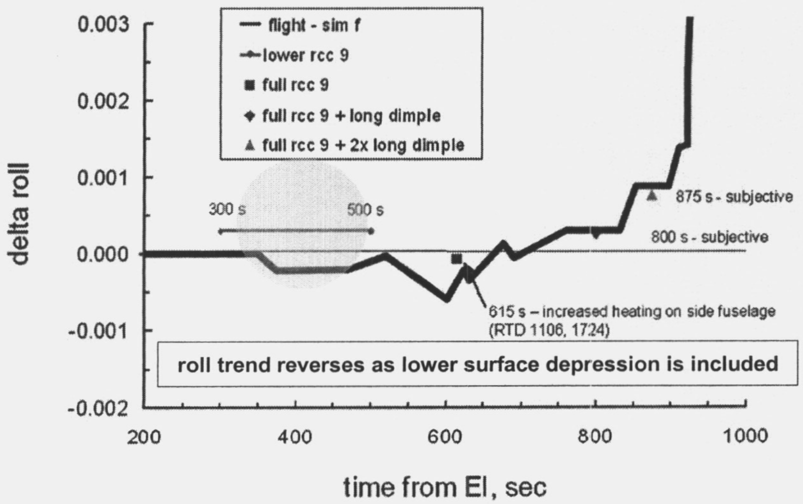


Thompson

Localized Damage To RCC Panel/Missing T-Seal

Experimental Aerodynamics

Progressive Damage Scenario - Roll

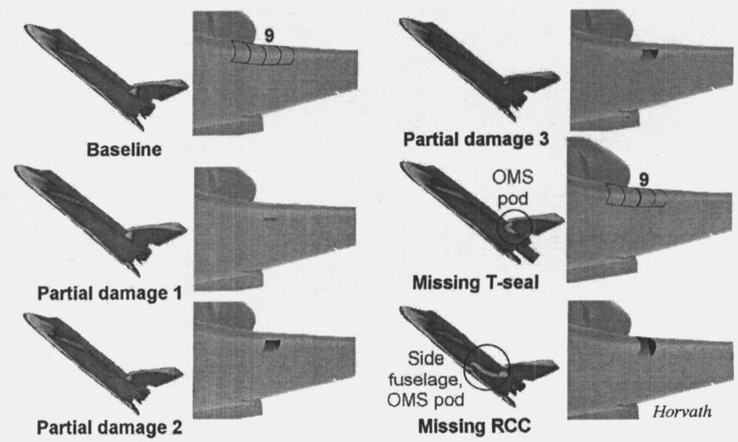


Brauckmann and Scallion

Experimental Aeroheating

Sensitivity of Orbiter Side Fuselage Heating to Partially Damaged RCC Panel 9

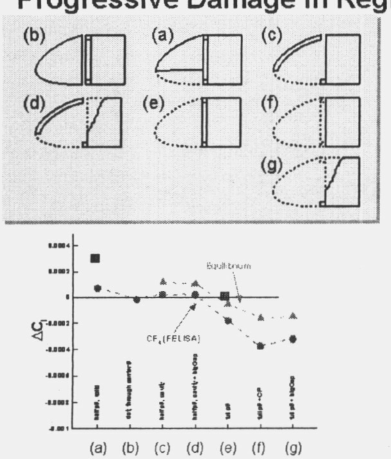
CF_4 $\gamma_{eff} = 1.13$ $\alpha = 40$ deg $Re_{\infty, L} = 0.4 \times 10^6$ $\beta = 0$ deg $\frac{\rho_2}{\rho_\infty} = 12$

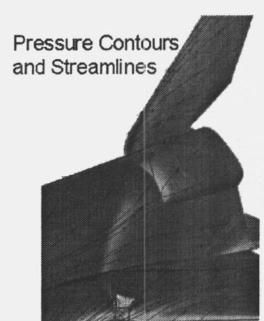


Horvath

Inviscid CFD (Aerodynamic)

Computational Aerodynamics
Progressive Damage in Region of RCC Panel 9



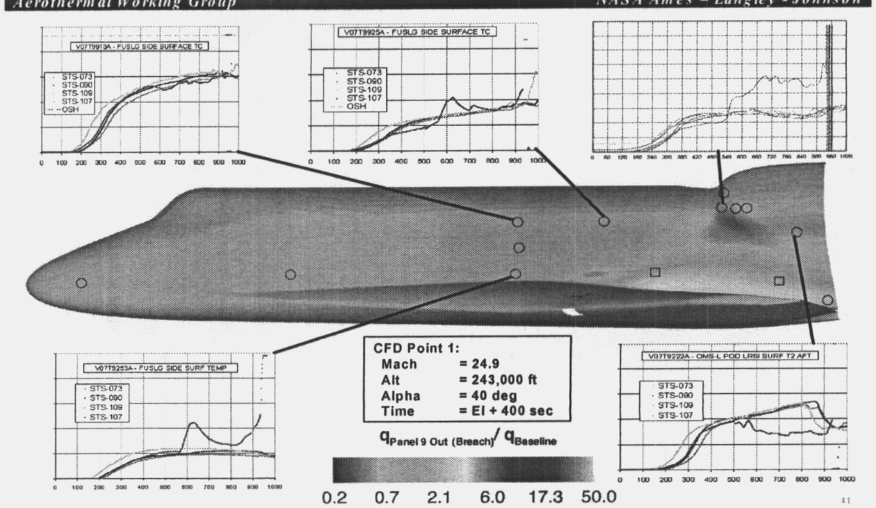


Half Panel 9, Upper Carrier Panel, Additional Leeside Material (d)

Bibb

Lower RCC Panel 9, Upper CP Out, Vented Side Walls Heat Flux Ratio – GASP Computations

Aerothermal Working Group — NASA Ames – Langley - Johnson



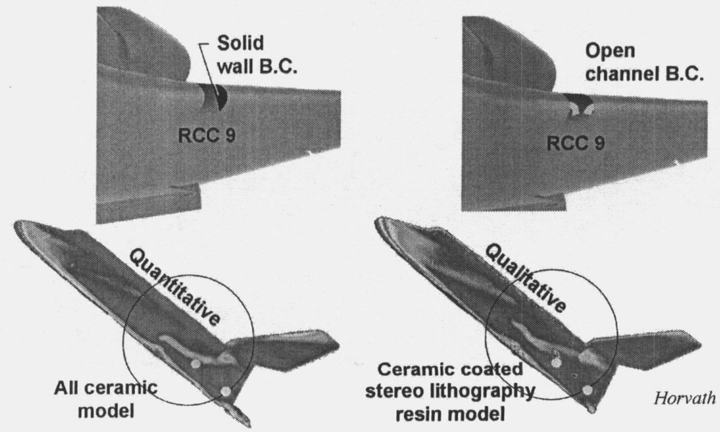
RCC Breach With Flow Ingestion

Experimental Aerodynamics

Experimental Aeroheating

Sensitivity of Orbiter Side Fuselage Thermal Mapping Pattern to Open/Closed Leading Edge RCC Channel

CF_4 $\gamma_{eff} = 1.13$ $\alpha = 40$ deg $Re_{\infty, L} = 0.4 \times 10^6$ $\beta = 0$ deg $\frac{\rho_2}{\rho_\infty} = 12$



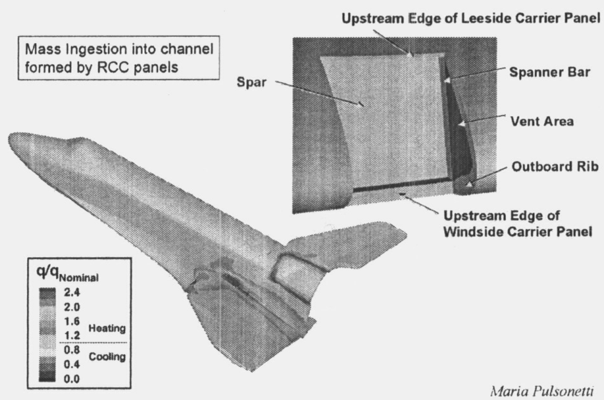
Horvath

Inviscid CFD

Viscous CFD (aerodynamic/aeroheating)

Ratio of Leeside Heating For Missing RCC Panel 9 (With Ingestion Into RCC Channel) to Nominal Heating

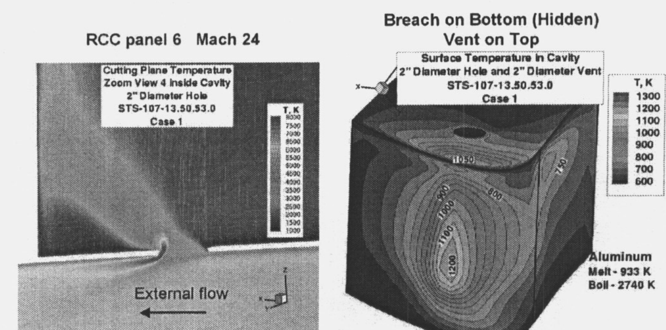
LAURA Solution Mach 25 Flight Finite-Rate Chemistry Laminar



Maria V. Pulsonetti

Flow Through Breach in Leading Edge

- Supplied mass and energy flux to interior as function of breach size.
- Boundary layer edge: not fully ingested for 2-inch diameter hole, impinges on lip for 4 inch diameter hole, fully ingested for 6 inch diameter hole.
- Non-orthogonal jets with fully-dissociated Oxygen impinge on interior walls.

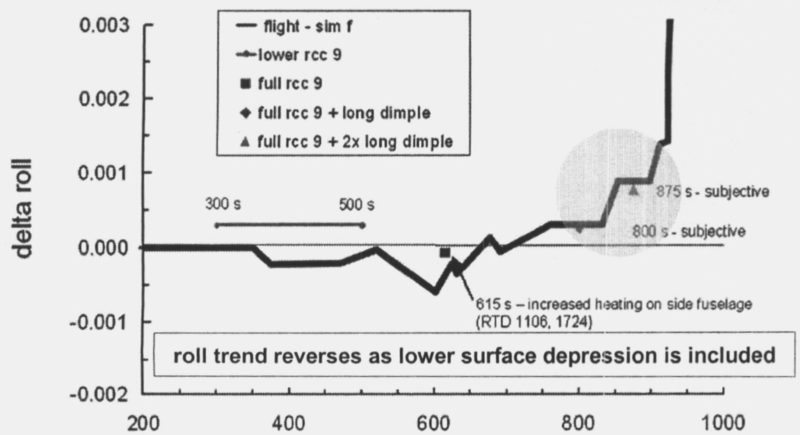


Gnoffo

Aero-Aerothermal Closure

Closure For Experimental Aerodynamics

Progressive Damage Scenario - Roll

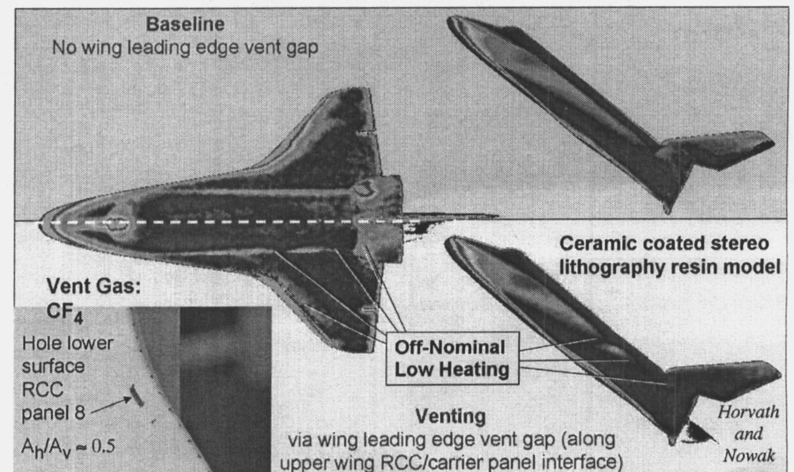


Brauckmann and Scallion

Closure For Experimental Aeroheating

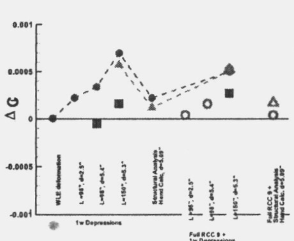
Sensitivity of Orbiter Side Fuselage/OMS Pod Heating Patterns to Gas Venting Along Wing Leeside Vent Gap

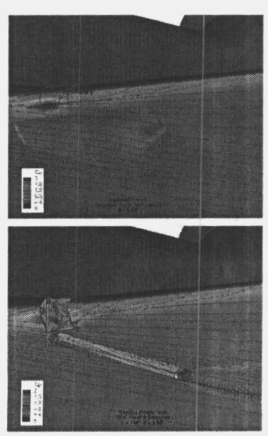
CF_4 $\gamma_{eff} = 1.13$ $\frac{\rho_2}{\rho_\infty} = 12$ $Re_{\infty,L} = 0.4 \times 10^6$ $\alpha = 40$ deg $\beta = 0$ deg



Closure For Inviscid CFD (Aerodynamic)

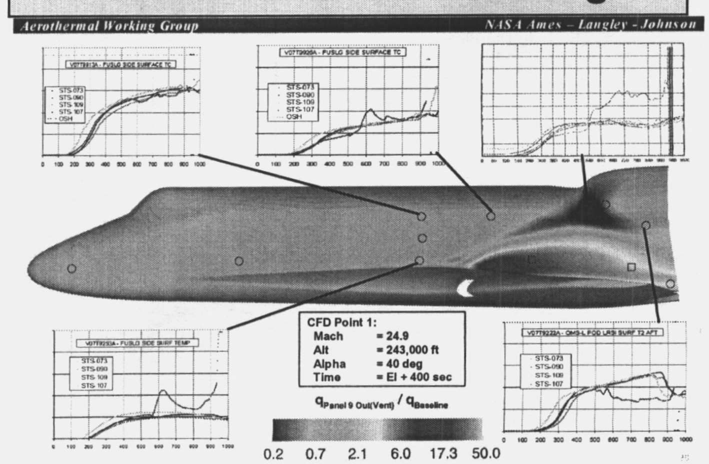
Computational Aerodynamics
Windside Surface Deformation





Bibb

Closure For Viscous CFD Aeroheating



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